Statement of Ms. Marjorie L. Tatro
Director of Fuel and Water Systems
Sandia National Laboratories

United States Senate
Committee on Appropriations
Subcommittee on Energy and Water Development
May 6, 2009

Introduction

Mr. Chairman, Senator Bennett, and distinguished members of the Subcommittee, thank you for the opportunity to testify this morning. I am Margie Tatro, Director of Fuel and Water Systems at Sandia National Laboratories. Sandia is a multi-program national security laboratory owned by the United States Government and operated by Sandia Corporation[1] for the National Nuclear Security Administration (NNSA). I am a Mechanical Engineer by training and I have worked in energy technologies for over 20 years.

Sandia has roles in the design, development, qualification, and certification of non-nuclear subsystems of nuclear warheads, nuclear nonproliferation, energy security, intelligence, defense, and homeland security. Sandia is proud of the considerable expertise it has achieved in the area of energy security, especially in understanding the relationship between national security and the energy enterprise.

Sandia is widely published in the energy and fuels research category. In fact, according to *Science Watch*[2], among institutions ranked by total citations of papers published between 1998 and 2008, none surpasses Sandia National Laboratories, with more than 4,100 citations to its 395 papers. In addition, Sandia ranks in the top 10 institutions when measured by citation impact. The area most widely cited during this ten-year period was combustion science followed by strong contributions in battery science and solar energy. Sandia is fortunate to have a talented multidisciplinary team of scientists and engineers who are dedicated to delivering “exceptional service in the national interest.”

Summary of Key Points

My statement today is summarized in four key points:

1. The U.S. economy and environment would benefit from investments in scalable technologies and processes for recycling of carbon dioxide (CO_2) as one option for addressing two critical, yet interrelated, challenges facing our nation and the world – stabilizing the concentration of CO_2 in our atmosphere and producing new supplies of liquid hydrocarbon fuels that help reduce our dependence on petroleum. Though I will describe efforts at Sandia focused on CO_2 recycling to address these challenges, an organized and focused national effort including

[1] Sandia Corporation is a subsidiary of the Lockheed Martin Corporation under Department of Energy prime contract number DE-AC04-94AL85000.

[2] *Science Watch* (2008), Nov/Dec Featured Analysis, http://sciencewatch.com/ana/fea/08novdecFea/ (Note that citation impact is measured by average number of citations per published paper.)

the establishment of a number of collaborative teams to explore these and other approaches would be prudent investments in the long-term interest of the nation.

2. Algae-based biofuels and synthetic fuels from solar energy are attractive because of the possibility of converting solar energy into liquid hydrocarbon fuels which are compatible with the *existing* infrastructure and at scales and efficiencies sufficient to meet large demands. Lifecycle efficiencies are important because they are indicators of the relative "size of the enterprise" necessary for large volume production. As important as efficiency, both options can recycle CO_2 back into fuel at rates faster than the biosphere takes up CO_2. Lastly, if CO_2 is extracted directly from the atmosphere, then we can produce high-efficiency, carbon-neutral fuels.
3. With the support of the Department of Energy (DOE) and others, Sandia is developing and applying science-based algae growth models and techno-economic tools to examine the best options for scaling up the production of algal biofuels. Sandia has also built a prototype "chemical heat engine" to split water and CO_2 using concentrating solar energy. This prototype is a critical step towards demonstrating the feasibility of making solar-based fuels without first making electricity. We are equally excited about a number of ideas for extracting CO_2 from the atmosphere. As excited as we are, we know of many others with similar enthusiasm and ready to make major contributions.
4. Other countries are exploring reuse and recycling of CO_2 and it would be unfortunate if the U.S. became dependent on imported technology in this critical area. This "grand challenge" has excited our team; indeed, I believe this, and sustainable energy research in general, is exciting to the next generation of engineers and scientists all across the nation.

Thinking Differently About Energy, Carbon and Security

Taking today's energy system in the U.S. as a whole, there are six major problems: (1) over 50% of primary energy resources are lost as waste heat and emissions during energy transformations and transport; (2) diverse and intermittent resources, such as wind, solar, and distributed generation, are difficult to accommodate; (3) the system relies on nature to close the cycle on waste byproducts such as used nuclear fuel, CO_2, and heat; (4) the infrastructure is limited in capacity, flexibility, reliability, and resiliency; (5) increased competition for finite petroleum and natural gas resources limits our foreign policy options and puts pressure on our economic and military resources; and (6) unpredictable energy prices create uncertainty and risk for all stakeholders (producers, suppliers, end-users, and policy makers).

As we strive to transition today's energy system to one that alleviates the problems mentioned above, we should keep the following requirements in mind:

- <u>Safety</u>: safely supplies energy services to the end user,
- <u>Security</u>: resists malevolently caused and weather or aging infrastructure -related disruptions and recovers quickly from any disruptions,
- <u>Reliability</u>: maintains delivery of energy services when and where needed,
- <u>Sustainability</u>: matches resources and delivery with needs for energy services for the entire duration of those needs with minimal waste, and

- Affordability: delivers energy services at the lowest predictable cost.

To meet the needs of future generations – and assuming a desire to stabilize CO_2 concentrations in the atmosphere and a continued demand for portable energy for transportation – the transformed energy system will be one that likely has five key elements: (1) its primary energy supply comes from persistent (preferably domestic) low-net-carbon energy resources; (2) its energy carrier conversion, as well as distribution and use, involves processes that are as efficient as practical; (3) it reuses or recycles resources in waste streams, particularly ones that have some inherent value such as residual energy or useful mass; (4) it uses liquid hydrocarbons[3] made from abundant and accessible carbon and hydrogen resources; and finally, (5) it has inherent storage to accommodate disruptions and makes maximum use of the existing energy infrastructure. The current national dialog focuses mostly on the first element and, unfortunately, very little on the other four.

We find making liquid hydrocarbon fuels from "recycled" CO_2 an intriguing prospect for enabling the above envisioned energy system as it would preserve the positive attributes of petroleum while eliminating most of the negatives, and at the same time using an abundant waste stream. Indeed, developing solar, wind, geothermal (and maybe nuclear) -driven processes that can efficiently, cost-effectively, and sustainably take the products of combustion, CO_2 and water, and recreate liquid hydrocarbon fuels would be an unparalleled achievement. Surmounting this challenge would go a long way toward solving the problem of finding domestic substitutes for petroleum which do not add more carbon to the atmosphere. Later in my statement, I will talk more about our ultimate vision of "recycling" CO_2 by extracting it directly from the atmosphere, thereby slowing the increases in the concentration of CO_2 in the atmosphere. We envision using the atmosphere as an efficient means for transporting the CO_2 from any source to the "recycle sink." But before doing this, a summary of the CO_2 "situation" is in order.

Carbon Management Options

Carbon dioxide is a by-product of energy conversion processes; it is emitted when fuel is combusted. In 2006, worldwide CO_2 emissions were 29.2 $GtCO_2$ (metric Gigatons of CO_2) with the U.S. being one of the largest contributors, adding 5.9 Gt in 2006[4]. The U.S. consumed 20.7 million barrels of oil per day in 2007. Note that a typical barrel of crude oil will produce 0.42 metric tons of CO_2 if combusted[5]. Of petroleum use in the U.S., 69% goes to transportation. The transportation sector in the U.S. contributed almost 2 Gt of CO_2 emissions to the atmosphere in 2006[6]. Since pre-industrial times the concentration of CO_2 has increased from roughly 280 parts per million by volume (ppmv) to approximately 385 ppmv[7].

---

3 Liquid hydrocarbons are easily distributed and used in the existing infrastructure, including the hundreds of millions of vehicles currently on the road with mean age of 8–9 years and median lifetimes of >17 years. Hydrocarbons can also provide inherent portable storage for intermittent sources such as solar and wind, especially in circumstances when those resources are not readily connected to the grid.

4 DOE Energy Information Administration (2006).

5 NETL (2008), "Storing CO_2 with Enhanced Oil Recovery," DOE/NETL-402/1312/02-07-08, 35.

6 DOE Energy Information Administration (2006).

7 http://www.noaanews.noaa.gov/stories2008/20080423_methane.html.

We now explore how recycling of CO_2 fits into carbon management options with the goal of reducing the growth of atmospheric CO_2 concentrations more broadly. We think of carbon management in terms of rebalancing the sources and sinks to and from the atmosphere – currently sources exceed sinks and this is why the concentration of CO_2 in the atmosphere is increasing. There are five elements in a carbon management tool box: (1) reduce, (2) extract, (3) reuse, (4) recycle, or (5) bury. There are three avenues to **reduce**: (i) reduce the demand for energy services (e.g, drive fewer miles); (ii) increase the efficiency in the energy conversion and transport processes; and, (iii) reduce the carbon intensity or CO_2 emitted per unit of primary energy. **Extract** comes into play as we begin to seriously think about active carbon management by capturing at the source, usually large stationary sources, such as coal-burning power plants. However, we can also conceive of extracting directly from the atmosphere, surface waters, or heavily distributed emitters. The **reuse** category presents several options, including enhanced oil recovery (EOR) as well as using the CO_2 as a "green" solvent in chemical processing, for dry ice in food processing, and for carbonation. The **recycle** category has received very little attention to date except indirectly through the production of bio-energy from biomass. Recycle is the category that is the principle focus of my statement today. The **bury** category is equivalent to sequestration – or the *storage* part of carbon capture and storage.

At present, industry has a variety of uses for CO_2, but the quantities are small. Some example uses are: neutralizing alkaline effluents in the chemical sector; making salicylic acid and aspirin in the pharmaceutical sector; chilling and carbonation in the food and beverage sector; balancing the pH in the pulp and paper sector; cooling and cleaning in the electronics sector; and as the fire suppression material in fire extinguishers[8,9]. The annual use of CO_2 for EOR in the U.S. is estimated at 0.04 Gt[10]. While "recycling" CO_2 as a feedstock for chemical production is an important use, the U.S. only consumed on the order of 0.11 Gt[11] of CO_2 in the 2003 timeframe; the largest use was to make urea. Furthermore, even if the top three U.S. produced chemicals (ethylene, propylene, and ethylene di-chloride) used CO_2 as the carbon source, they would only consume another 0.14 Gt[12]. The one "chemical" product that does scale to large quantities is fuels. If we were to use CO_2 as the carbon source to generate the equivalent of our petroleum consumption, 3.0 Gt CO_2 of would be consumed or recycled[13].

Technologies that can recycle CO_2 into liquid hydrocarbons are attractive propositions. Liquid hydrocarbon fuels are ideal energy carriers and exceptionally convenient to store, transport, and transfer due to their liquid form and high energy-density by mass and volume. While greater electrification of the transportation fleet will almost certainly be an important element of a trans-

8 Gobina, E. (2004), "Carbon Dioxide Utilization and Recovery," BCC Report E-131, Business Communications Co., Norwalk, CT.

9 "Carbon Management: Implications for R & D in the Chemical Sciences and Technology" (A Workshop Report to the Chemical Sciences Roundtable), http://www.nap.edu/catalog/10153.html.

10 DOE/NETL-402/1312/02-07-08, "Storing CO_2 with Enhanced Oil Recovery," February 2008, pp 45.

11 Beckman, E.J. (2003), "Green Chemical Processing Using CO_2," Ind. Eng. Chem. Res., *42* (8), pp 1598–1602.

12 Chemical & Engineering News, July 2, 2007.

13 For this conversion, we assumed 20.7 million barrels/day, 136 kg/barrel, and 83% carbon in petroleum by weight.

formed energy system, routes to creating liquid hydrocarbons which have properties equivalent to gasoline, diesel, and jet fuel should not be ignored.

Efficiency Matters

We are reminded that petroleum, coal, natural gas, and unconventional oil are in fact "stored sunlight" and "sequestered carbon"[14]. We tend to categorize fossil fuels as primary energy resources when, in fact, they are energy carriers, which are the result of an inefficient set of conversions of energy and mass fluxes integrated over a very long time. The process began many millions of years ago with a biological organism capturing sunlight (solar flux) and storing the sun's energy by using it to drive chemical reactions of CO_2 and H_2O to higher energy hydrocarbons and oxygen (photosynthesis). A small fraction of the plant matter was then converted over time by heat and pressure to coal, oil, and natural gas. The overall efficiency in this naturally occurring process was quite low.

Efficiencies are important because they provide an indicator of the "scale of the enterprise" needed to convert solar energy into fuels, and are therefore one indicator of relative costs. For oil, the sunlight-to-stored energy can be estimated[14] to be only about 0.0002% efficient, with large error bars on that estimate. Another way to look at this efficiency is to estimate energy and carbon fluxes. This estimate reveals possible efficiencies of algal biofuels of nearly 3% and solar synthetic fuels of 5%–10% (though large uncertainties exist because neither technology has been proven at large scale). Assuming an average lifecycle efficiency of 5% (and average solar energy of 200 watts per square meter), producing the equivalent of the U.S. petroleum usage of 20.7 million barrels of oil equivalent per day using solar energy would require approximately 28 million acres of land. In contrast, total U.S. land is roughly 2 billion acres and paved highways in the U.S. cover approximately 19 million acres.

Bio-energy from biomass or biofuels can be thought of as a modern-day approach to improve upon nature's inefficient process to create petroleum. As with fossil fuels, the starting point is the photosynthetic conversion of CO_2 and H_2O to hydrocarbons in the form of carbohydrates and lipids. The efficiency of this process is significantly better than that for petroleum and is estimated in our energy flux analysis to be approximately 3%. Additional chemical or biological steps are then undertaken to produce a liquid hydrocarbon fuel. Algae are attractive as a fuel feedstock because their production can potentially avoid competition with agricultural lands for food and feed production and can use nonfresh water resources. CO_2 is added to the water as a nutrient to achieve high productivity from algae.

Taking another step further towards increasing the efficiency and directly recycling CO_2 into synthetic fuels can be thought of as emulating the effectiveness of nature's choice to store solar energy by converting CO_2 and H_2O into high energy-density hydrocarbons[15]. Synthetic processes bypass the biological steps that lead to low energy and carbon fluxes and low efficiencies. A

---

[14] Dukes, J.S. (2003), "Burning Buried Sunshine: Human Consumption of Ancient Solar Energy." *Climatic Change*, 61, 31.

[15] Nature's preferred energy storage means is fat or oil, both which have an energy density of approximately 39 MJ/kg, fairly close to that of gasoline, diesel, and jet fuels at approximately 45 MJ/kg.

worthy target for synthetic routes would be to achieve lifecycle efficiencies of approximately 10%.

A known option would be to assemble a system based on solar photovoltaics using electrolysis of water to make hydrogen (H_2), then reacting the H_2 with CO_2. Such a system could be assembled from commercially available components (though none is currently economically viable) and could achieve approximately 5% efficiency, with a limiting factor being the initial step of converting solar energy to electricity.

It is these relatively high efficiencies and minimal land requirements that generate our excitement about the prospects for recycling CO_2 into algae-based fuels and solar-based fuels. Creating technologies that are capable of extracting CO_2 from the atmosphere is also important to make these fuels "carbon neutral." In the remainder of this document, we delve more deeply into the three types of technologies that are key enablers for the recycling of CO_2: (1) algae-based fuels, (2) direct synthesis of fuels from CO_2 and water including "Sunshine-to-Petrol," and (3) extraction of CO_2 from the air. For each technology, we will present a few activities both domestically and abroad, efforts at Sandia that that indicate the promise of such options, and current technological and economic challenges with possible timelines.

Algal Biofuels

Current Activities

From 1978 to 1996, the Department of Energy's (DOE) Aquatic Species Program represented the most comprehensive research effort to date on fuels from algae. Headed by National Renewable Energy Laboratory (NREL), the program also supported fundamental research at many academic institutions[16]. Since 2007, Sandia has partnered with NREL to develop an algal technology roadmap for DOE's Office of Energy Efficiency and Renewable Energy and Office of Biomass Program. The roadmap will identify and prioritize key biological and engineering hurdles that must be overcome to achieve cost-effective production of algal-based biofuels and coproducts. It will also suggest research strategies to address these barriers. The DOE's National Energy Technology Laboratory has partnerships in place with coal-fired power plant operators to explore the option of growing algae in cooling-water ponds.

The prospective value of biofuels from algae has been recognized internationally not only by the global research community, but also a range of commercial sectors including transportation energy, agriculture, and biotechnology, and the venture capital community. A large cadre of venture-backed start-ups working on algal biofuels has emerged over the last few years and larger companies are also getting involved in algae. Meanwhile, the global research community has moved quickly to embrace the challenges presented by producing algal biofuels at scale as witnessed by the dramatic acceleration in conferences on algal biofuels and the formation of public-private partnerships and consortia. This is occurring in the U.S., Israel, China, India, France, the Netherlands, and Denmark.

---

16 Sheehan, J., T. Dunahay, J. Benemann and P. Roessler (1998), "A look back at the U.S. Department of Energy's Aquatic Species Program-Biodiesel from Algae," https://www.nrel.gov/docs/legosti/fy98/24190.pdf.

It is estimated that the production of 2.4 million barrels of gasoline with algal oil would consume 1.5 billion tons of CO_2, or 43% of total 2008 U.S. emissions from stationary sources[17].

Sandia's Efforts

The algal biofuels program at Sandia National Laboratories leverages technical strengths in analytical chemistry and applied biology, computational fluid dynamics, and integrated systems analysis – including developing and applying biofuels supply chain models aimed at identifying barriers to cost-effective production of algal biofuels. Sandia's efforts include developing and applying analytical tools to characterize algae gene and protein networks and to monitor algae health. In applied biology, Sandia develops fundamental understanding of algal physiology through genetic engineering, enzyme engineering, and identifying biomarkers and strategies for monitoring biomarkers relevant to biomass cultivation and fuel production.

In the area of computational fluid dynamics, Sandia has developed an algae growth kinetic model in a computational fluid mechanics framework as an engineering tool to develop cultivation strategies for algae – both open ponds as well as photobioreactors.[18] Sandia also owns and operates a facility with algal growth tanks that are equipped with sensors that can be used for validating production models. Systems dynamics models also help us understand the relationship between water supplies, evaporation, and algae production.

In related efforts, Sandia is an active member of the Joint Bioenergy Institute and contributes towards biomass deconstruction and pretreatment for cellulosic biofuels. Our world-class Combustion Research Facility and Center for Integrated Nanotechnologies provide fundamental science understanding in areas of alternative transportation fuels.

Techno-Economic Challenges

Scientific discovery must be complemented by engineering and techno-economic evaluations to enable affordable, scalable algal biofuels. Open literature has reported algal-derived crude oil at a cost spanning over three orders of magnitude ($1 to $1,000 per gallon of triglyceride), with the greatest uncertainties in estimates of facility and operating costs[19]. Investment in every step of the supply chain, from understanding algal biology, strain selection and optimization, cultivation at scale, harvesting, dewatering, and extraction of the hydrocarbons from the algal biomass is needed. As such, both the DOE and the U. S. Department of Agriculture have called for algal biomass funding opportunities to accelerate the R&D cycle.

The DOE has commissioned Sandia and NREL to jointly create a systems dynamics model for carrying out techno-economic analyses of algal fuel development strategies. To be cost competitive, the process must be able to tolerate solar energy variability and energy and water consump-

---

[17] National Carbon Explorer 2008 CO_2 Stationary Source Atlas, http://www.natcarb.org.

[18] Boriah, V. and S.C. James, "Optimizing Algae Growth in an Open-Channel Raceway," Algae Biomass Summit, 2008.

[19] Pienkos, P., "Historical Overview of Algal Biofuel Technoeconomic Analyses," National Algal Biofuels Technology Roadmap, December 9-10, 2008.

tion must be lowered. In evaluating resource constraints, it is clear that the availability of water and CO_2 use will limit the locality of sustainable algal biofuel production[20].

While algal biofuels present an opportunity that will require some time (roughly 10 years) to realize, they are a key component in the U.S. biofuels strategy. Transportation fuels produced from algal biomass are compatible with our existing transportation fuel infrastructure, can recycle CO_2 waste streams, and can be produced on nonarable land with impaired water sources.

Synthetic Fuels from CO_2 and Water

Current Activities

Work on alternative fuels has been ongoing for much of the last century; the chemistry and technology for converting fossil-energy resources such as coal is well established and has been practiced commercially in parts of the world for many decades. In contrast, the science and technology for producing hydrocarbon fuels from persistent energy sources (e.g, solar, wind, geothermal, and nuclear power) in a sustainable fashion, is relatively immature. Investments and advances in biofuels and H_2 are ongoing. Because H_2 is a critical feedstock for making liquid fuels, research efforts aimed at the renewable production of H_2 also further the vision of recycling CO_2 into fuels.

Work on CO_2 reuse and recycling has been less visible, but nonetheless efforts are underway around the world. Many of these efforts have been directed towards applications that could consume only a very small fraction of the CO_2 produced through the combustion of fossil fuels, for example supercritical solvents and production of higher-value chemicals.

The primary challenge to recycling CO_2 as a chemical feedstock for either fuels or chemicals and pharmaceuticals is the energy cost and efficiency for splitting (activating) the very stable, CO_2 molecule; furthermore, that energy source must itself have a very low carbon intensity. Achieving such a technology would open the door to using CO_2 as a feedstock for liquid fuels as well as for polymers, plastics, carbonates, and numerous other valuable chemicals and materials (i.e., light-weight carbon composites and carbon-nanotube-based materials).

One basic approach for re-energizing the CO_2 molecule into a useful product has been to react it with another energetic molecule such as H_2. Both Korea and Japan have sponsored work in this area. For example, Japan's Mitsui Chemicals recently announced their intent to make methanol from captured CO_2 and H_2. Additionally, efforts have been initiated in Iceland to commercialize the production of methanol from CO_2 and H_2 from geothermal-powered electrolysis of water.

An alternative means is to use electricity to directly re-energize CO_2. This is analogous to splitting water by electrolysis to make H_2. Hybrid biological and electrical approaches are showing progress. Examples include work at Princeton and announcements from the private sector, such as Carbon Sciences. However, we emphasize that unlike splitting water and making H_2, there are

[20] Pate, R., "Algal Biofuels Techno-Economic Modeling & Assessment: Taking a Broad Systems Perspective," National Algal Biofuels Technology Roadmap, December 9–10, 2008.

no commercialized technologies that have been developed to directly activate CO_2 and only few research efforts around the world are underway.

Finally the greatest amount of work has been carried out on approaches that can broadly be categorized as artificial photosynthesis. These most closely emulate the process of photosynthesis in harvesting the energy from sunlight to generate electrons and protons to reduce the CO_2. The work ranges from efforts to engineer new devices using the tools of nanotechnology to efforts to replicate natural systems removed from a living organism. Genetic engineering of living organisms is a related approach.

Sandia's Efforts

At Sandia, we have assembled a multi-disciplinary team of scientists and engineers, including a number of university partners to explore a promising new approach to directly activating CO_2 using concentrated solar energy. A novel new "heat engine" concept[21] breaks a carbon-oxygen bond in the CO_2 to form carbon monoxide and oxygen in two distinct steps at two different temperatures. Energy for the high-temperature step comes from the sun. This thermochemical approach appears suited to the production of both H_2 from water and carbon monoxide from CO_2. This process, which we call "Sunshine-to-Petrol," avoids converting the principal energy source (e.g, solar energy) to electricity thereby providing an avenue to potentially higher efficiency than the alternatives. The Sandia team built a thermochemical "heat engine" and named it the Counter-Rotating Ring Receiver Reactor Recuperator or "CR5." The CR5 is a solar receiver which converts concentrated solar energy into thermal energy. The rings counter-rotate. It is a reactor, actually two reactors – thermal reduction and oxygen extracting. Lastly, it is a recuperator – to minimize heat losses and maximize efficiency. If suitable materials can be developed and the design challenges can be met, the CR5 heat engine concept appears to provide an integrated approach for potentially efficient and affordable solar-activated CO_2 and water. However, this system imposes unique requirements on materials.

Techno-Economic Challenges (for "Sunshine-to-Petrol")

The CR5 involves numerous design issues and tradeoffs. It places extraordinary demands on materials and involves high-temperature moving parts. Ensuring we have suitable materials will require a substantial degree of fundamental understanding of the chemical and cycle thermodynamics. To establish the practicality of the CR5 concept, we are experimentally evaluating materials, exploring the thermodynamics and kinetics of the materials, evaluating heat and mass flows within the device, and assessing a number of integrated system designs. We expect a focused effort to have a reasonable probability of success. We envision a series of improved engine and system designs. Successful progress would consist of continuously improved generations of prototypes and Sunshine-to-Petrol systems resulting in a new generation every three years with significant improvements in performance, durability, and cost. The system would produce gasoline or diesel or jet fuel as the end product. Our targets are **efficiency**: 10% system and lifecycle effi-

[21] Diver, R.B., J.E. Miller, M.E. Allendorf, N.P. Siegel, R.E. Hogan (2008), "Solar Thermochemical Water-Splitting Ferrite-Cycle Heat Engines," *Journal of Solar Energy Engineering*, November 2008, vol. 130, issue 4 041001.

ciency[22], **durability**: five years of operation for the reactive rings and twenty years for the mirrors and the rest of the engine, and of course **cost**: competitive with all low-carbon alternatives to petroleum, but perhaps no more than $5.00/gallon of gasoline. With that schedule of improvements, the technology should be market-ready in less than two decades. For a concept as new as the CR5 and Sunshine-to-Petrol, we believe that this would be an aggressive schedule.

Extracting CO_2 From Air

Current Activities

To achieve the promise of recycling CO_2 into renewable and sustainable liquid hydrocarbons through either algae-based or solar-based fuels requires extraction of CO_2 directly from the air. The extraction of CO_2 from air has received relatively little attention. However, with the announcement of the Earth Challenge Prize[23], by Richard Branson of Virgin Atlantic, a number of small start-up companies are taking on this challenge. Small-scale CO_2 capture within submarines and spacecraft is well known. In these applications however, the CO_2 was generally not used for further purposes and release from the capture agent had not been a deliberate design parameter. Klaus Lackner of Columbia University authored several studies on CO_2 capture, with many compelling arguments and has been awarded a patent, with Allen Wright from Global Research Technologies for their novel concept. A project initiated at Carnegie Melon[24] demonstrated the general feasibility of CO_2 capture from air using an aqueous NaOH spray. Lab-scale units have been built by teams at the University of Calgary in Alberta, Canada and at the Swiss Federal Institute of Technology in Zurich. "Green Freedom" efforts at Los Alamos National Laboratory are addressing the capture of CO_2 from air flows of cooling towers, such as those at nuclear power plants.

While conversion of atmospheric CO_2 into a pure feedstock for hydrocarbon fuels synthesis is unquestionably feasible at the bench scale, estimations suggest prohibitively high costs and very low efficiencies relative to what is theoretically possible. Hence, proven methods needed to concentrate large amounts of CO_2 at affordable costs and high efficiency do not exist. CO_2 capture in a specially designed material is analogous to H_2 storage, where the design consideration is to be able to grab it tight enough, but not so tight that it cannot be released at the appropriate time. Most materials identified have a large energetic cost penalty to remove the CO_2 or very slow kinetics at the uptake. What is needed is fast kinetics at the uptake and low energy for release, but not too low. Industrial-scale capture will also entail the processing of large volumes of air through the capture media.

---

[22] Lifecycle efficiency includes solar energy to gasoline conversion and takes into account the energy required to manufacture the components of the system. Some refer to this as "rays-to-tank" efficiency.

[23] Sponsors are seeking method that will remove at least one billion tons of CO_2 per year from the atmosphere, and the winner will receive $25M.

[24] Stolaroff, J.K., D.W. Kieth, and G.V. Lowry (2008), "Carbon Dioxide Capture from Atmospheric Air Using Sodium Hydroxide Spray," *Environmental Science and Technology*, 42, 2728–2735.

Sandia's Efforts

At Sandia, we have explored the plausibility of large-scale capture from air and a number of new solid sorbents. Our investigations indicate, among other things, that at 4.5 meters/second wind speeds, the cross-sectional area needed to collect enough CO_2 to produce 20.7 millions barrels of oil is between 14,000–36,000 acres, corresponding to capture efficiencies[25] of 50% and 20%, respectively. Sandia has been collaborating with researchers at the National Energy Technology Laboratory to explore the feasibility of a number of ideas for capturing CO_2 from the atmosphere.

Techno-Economic Challenges

Our analysis suggests the following technical challenges must be met before capture of atmospheric CO_2 for conversion to hydrocarbon fuels or for other re-use options can be considered plausible at the industrial scale: (1) low-energy air processing approaches to assure effective air flows through CO_2 sorbent media to ensure high production rates; (2) durable and easily manufactured materials that readily capture as well as release CO_2 from air at industrial scales; (3) less expensive solid or liquid CO_2 sorbents that have high capacities and are stable over very many catch-and-release cycles; and (4) bench-scale testing and later, pilot-scale demonstrations of atmospheric CO_2 capture approaches.

We expect a focused effort for a decade would have a good probability for success, depending on what cost the market can bear. Note that a capture cost of $50–$75 per metric ton of CO_2 would add only $0.44–$0.66 to the cost of a gallon of gasoline. This seems achievable.

Conclusion

The possibility of making liquid fuels from domestic resources that are compatible with our existing transportation energy infrastructure while recycling CO_2 is exciting and real. Because so much of today's CO_2 emissions come from the burning of fossil fuels, it seems natural for us to use this waste stream to produce alternative fuels for future generations. Ideas including those described in this document – algal-based biofuels, solar or other renewable-based fuels, and extraction of CO_2 from air – require investments to prove their technical and economic viability at large scale.

Collaborative teams from across the nation, and the world, are already developing ideas worth pursuing, but the efforts are currently splintered; we must act now to stimulate this area of research and development. Other countries are exploring the re-use and recycling of CO_2 and it would be unfortunate if the U.S. became dependent on imported technology or imported alternative fuels in this critical area.

Let me conclude by noting a caution from the technology-policy interface perspective. Carbon management policies that might inadvertently create disincentives for those who pursue the idea of CO_2 recycling could be detrimental to innovation and commercialization of technologies in this area. Policy experts may want to explore the implications of currently proposed actions from this perspective.

---

[25] Capture efficiency is the percent of CO_2 extracted. For example, 50% at 400 ppmv in the air stream would leave 200 ppmv in the air stream after passing through the collection media.

Marjorie (Margie) L. Tatro

Director of Fuel and Water Systems

Sandia National Laboratories

Telephone (505) 844-3154; Fax (505)284-5406

mltatro@sandia.gov

Margie currently leads a group of approximately 200 people working on behalf of the nation's taxpayers to make the nation's energy and water systems safer, more secure, more reliable, more sustainable, and cost effective. She is responsible for a $90M portfolio of programs that include fossil energy, renewable energy, and energy storage technologies, as well as energy efficiency, transportation fuels, and energy infrastructure research. In addition, Margie is responsible for water safety, security and sustainability efforts including work to improve water treatment technologies as well as the identification of water-energy challenges and research opportunities.

Margie holds B.S. and M.S. degrees in mechanical engineering from the University of California, Davis and the University of New Mexico and has been employed by Sandia National Labs since 1985. She has worked in renewable energy research, facilities design, software design, energy reliability and infrastructure protection groups while at Sandia. She is a native of Los Alamos, New Mexico.

Below are some of her presentations and papers:

1. A Dialogue on the Nation's Energy Future: Exploring Common Ground, 2009
2. Fuel and Water Systems for the 21st Century, M. M. Hightower, M. L. Tatro, 2009
3. Transition to Low Carbon Energy Solutions: Integrating Renewables, 2008
4. The Perplexing Energy Water Nexus, 2008
5. Refueling the Nation: An Energy Surety Approach, R. D. Robinett III, M. L. Tatro, 2008
6. Risk Assessment Methodologies and Their Application to Infrastructure and Cyber Security, J. L. Mitchiner, M. L. Tatro, 2007
7. Energy Surety and Challenges at the Intersection of Energy and Water, 2007
8. Realizing North America's Energy Security for the Future, M. L. Tatro, 2007
9. Energy Surety and Challenges at the Intersection of Energy and Water, 2007
10. In Search of Synergy Among Electric Power, Hydrocarbon Fuels, and the Environment, 2006
11. Energy Futures: A Look At Renewable Energy Challenges and Technologies, 2006
12. Realizing America's Energy Security for Tomorrow, M. L. Tatro, 2006
13. Energy Futures – A Look at Renewable Energy Challenges and Technologies, 2006
14. Toward an Energy Surety Future, M. L. Tatro, J. M. Covan, R. D. Robinett III, G. W. Kuswa, D. Menicucci, S. A. Jones, 2005
15. The Nexus Between Renewable Energy and National Security, 2005
16. Ensuring the Security, Safety, and Reliability of the U.S. Energy Infrastructure, 2004